NOAA SECTORAL APPLICATIONS RESEARCH PROGRAM (SARP)
PROJECT ANNUAL REPORT

PROJECT TITLE
USING NOAA CLIMATE FORECASTS WITH HYDROLOGIC ASSESSMENT TO REDUCE DROUGHT VULNERABILITY AND IMPROVE WATER MANAGEMENT IN WASHINGTON STATE

INVESTIGATORS
PI: Dr. Anne C. Steinemann; Co-PI: Dr. Andrew W. Wood

Dr. Anne C. Steinemann
Professor
Deptartment of Civil and Environmental Engineering
Evans School of Public Affairs
University of Washington, Box 352700
Seattle, WA 98195
Tel: 206-616-2661
e-mail: acstein@u.washington.edu

Dr. Andrew W. Wood
Research Assistant Professor
Department of Civil and Environmental Engineering
University of Washington, Box 352700
Seattle, WA 98195
Tel: 206-543-5856

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I. PRELIMINARY MATERIALS

A Project Abstract

Droughts are the nation's most costly natural disaster. In Washington State, this year's drought inflicted more than $300 million in damage to the agricultural sector, and halved the expected summer runoff that feeds the state economy. State-of-the-art climate forecasts, such as the NOAA CPC seasonal outlooks, offer the potential to mitigate drought damages through advance warning. Yet this potential is largely untapped by water managers; a gap remains between forecast products and their applications, often due to socio-organizational factors. This study will bridge that gap by working directly with users in the transition of NOAA climate forecasts,

coupled with hydrologic assessments, to water resources operations and drought management. Our focus is high stakes and highly drought-vulnerable Yakima River Basin, whose irrigated crops represent the largest agricultural value in the state. Irrigators depend on water from the Yakima Project, operated by the U.S. Bureau of Reclamation (USBR), which issues hydrologic forecasts that could benefit from improved climate information. The PIs will work with USBR to integrate NOAA climate forecast information into short-term and long-term water resources decisions through the UW west-wide streamflow forecasting system. In addition, the system used for the Yakima River basin will extend to the entire state of Washington to improve drought preparedness and response. Here, the PIs will work with the Washington State Department of Ecology (DOE), which has statewide drought decision-making authority, to implement a pilot application in support of the National Integrated Drought Information System (NIDIS), useful to broader efforts of the Western Governors' Association (WGA). Letters of support are provided by USBR and DOE. The work in the Yakima and the State will address these scientific questions, among others: How can NOAA climate forecast products be effectively translated and integrated into decision-making to reduce the vulnerability and impacts of drought? In turn, how can a process of working with stakeholders (e.g., water managers) be developed that will help to promote the integration of forecast information into decision-making? Expected benefits of the project include improved water management and drought mitigation in a key socio-economic sector and throughout Washington State, improved understanding of how to integrate NOAA climate forecast products into water resources decision-making, and a model implementation of climate and hydrologic forecasts in a statewide drought plan and NIDIS application. In addition, because the Yakima River basin exemplifies many water management challenges and conflicts across the U.S., successful transition of NOAA products in this case study is expected to generate broader lessons and national attention.

B Objective of Research Project

NOAA is increasingly being called upon to demonstrate that its products are useful for decision support purposes. The proposed project addresses this objective by posing the following science and applications questions:

- How can NOAA climate forecast products be effectively translated and integrated into decision-making to reduce the vulnerability and impacts of drought? For instance, how can advanced hydrologic prediction methods, which use state-of-the-art NOAA climate forecasts, result in improved seasonal streamflow forecasts and in turn more efficient water management?
- How can a process of working with stakeholders (e.g., water managers) be developed that will help to promote the integration of forecast information into decision-making? For instance, how can we more effectively bridge the gap between forecasts and their potential beneficial uses, through a process of understanding socio-organizational factors, opportunities and barriers?

We address the above questions by integrating NOAA climate forecast products with advanced hydrologic assessments through an advanced experimental hydrologic forecast system for the western U.S. that incorporates a semi-distributed hydrologic model. A key aspect of this project will be close interaction with our operations partners, and the exploration of advanced forecast products within their operational water management decision process. To do so, we will work directly with the USBR and DOE offices to adapt forecast products into formats that are most useful for their operations. The experience of the PIs is that direct interaction with operations staff in their environment is essential to successful communication of research products to operations. Therefore, we intend to go well beyond simply providing access to forecast products, and will focus on development of interfaces that will facilitate use of advanced hydrology forecast products into our operations partners' decision process.

C Approach

The primary focus of this research is on integration of NOAA products and research results into water resources decision support. We propose to use NCEP Climate Prediction Center (CPC) 15-day and seasonal climate forecasts and derived hydrologic forecasts in a partnership with two operational water management agencies – the U.S. Bureau of Reclamation, which has operational responsibilities within the Yakima River basin, and the State of Washington Department of Ecology, which has decision authority for the State of Washington. PI Wood will tailor prior and existing research in the UW west-wide hydrologic forecast system to both the State of Washington and the Yakima R. basin focus area, to produce operational Yakima R. basin streamflow forecasts (for input to USBR's water management software) and spatial hydrologic forecasts, and a high resolution State of Washington hydrologic monitoring system.

The user interaction process will follow these general steps (detailed in project proposal), which the PI developed and implemented in previous applications with water managers: 1. Specify Decision Context. 2. Understand Organizational Context. 3. Assess Potential Benefits/Costs. 4. Ensure Project Feasibility. 5. Specify Products. 6. Use Products, Obtain Feedback, Revise. 7. Evaluate Forecasts. The evaluation process will assess the relative benefits/costs of the new information relative to existing information and standard operating procedures. Three operational scenarios for evaluations will be conducted: retrospective, real-time, and prospective. An overall performance goal of the proposed activities is the integration of various NOAA products into the operation, planning, and decision-making activities of our partner agencies. Our success in accomplishing this goal will depend, to a large extent, on successful progress on measures that are coupled with the water management objectives of our user communities. Accordingly, we have developed evaluation measures to track performance in three dimensions: (a) forecast accuracy and decision support performance, (b) user acceptance and organizational assimilation, and (c) research team management.

D Description of any matching funds/activities used in this project

The work draws heavily from previous and ongoing hydrologic modeling and prediction research funded by NOAA (via CPO's CPPA and CDEP programs) and other agencies, this project will focus on transition of these NOAA products and research results to operations, rather than new technological developments. In addition, we have leveraged educational outreach resources provided by the University of Washington Water Center, which the PI directs (see http://water.washington.edu). Additional funding was received from the State of Washington for activities that support SARP goals.

II. ACCOMPLISHMENTS

A. Brief discussion of project timeline and tasks accomplished. Include a discussion of data collected, models developed or augmented, fieldwork undertaken, or analysis and/or evaluation undertaken, workshops held, training or other capacity building activities implemented.

Project tasks (as outlined in the proposal), and activities completed to date, are described below.

TASK 1 (COMPLETED): **Monitoring**: A statewide hydrologic monitoring system has been implemented using the VIC hydrologic model at 1/16 degree (about 6 km grid mesh). This system provides real-time, daily updating analyses (maps, datasets, and timeseries of hydrologic variables) that characterize hydrologic conditions throughout the state, presented via a website, the preliminary version of which is shown in Figure 1. It also encompasses the weekly update of the drought status in the terms of drought indices such as Palmer Drought Severity Index (PDSI), Palmer Hydrologic Drought Index (PHDI), Crop Moisture Index (CMI) and Z Index (ZIND) and the daily update of 1, 2, 3, 6, 9, 12, 24, and 36 month averaged value of Standardized Precipitation Index (SPI) and Standardized Runoff Index (SRI). This information not only helps track the long term and short term drought conditions but also to characterize drought events (Figure 2). Figure 3 is an example of a timeseries product from the website that is pertinent to state level monitoring of Water Resources Inventory Areas (WRIAs). The system is now being transitioned to run operationally in the office of the Washington State Climatologist.

TASK 2 (CURRENT): **Streamflow simulation**: In the focus region of the Yakima River basin, the flow routing network (shown in Figure 4) has been developed and streamflow simulations for 10 of the anticipated 12 locations are being calibrated (Figure 5 shows early results for three locations). Although the calibration results for the upstream basin gauging stations are fairly good, calibration efforts for streamflows further downstream of the basin continue. In connection with this effort, we have assessed the model performance in simulating the snow accumulation and snow melt in Yakima basin with several approaches for estimating meteorological model forcings.

TASK 3 (CURRENT): **Prediction**: Work has begun to prepare the statewide monitoring system with the embedded Yakima R. focus region as the initializing state for 2 week to 1 year lead hydrologic forecasts, from which it will be possible to obtain drought onset and recovery predictions. These will be based on both ensemble streamflow prediction (ESP) techniques advanced by the National Weather Service, and NCEP Climate Prediction Center seasonal outlooks. To this end, the Climate Prediction Center's new consolidated forecast (not previously available to the public) has been obtained and is being evaluated in the Washington State domain. In addition, preliminary work to develop methods for forecast error reduction has resulted in a submitted paper (listed below). We are also interested in evaluating the drought prediction skill derived solely from the initial hydrologic conditions (such as snowpack and soil moisture). Depending on the season, the initial hydrologic conditions control the development of the hydrologic conditions in the future. We have used the NWS ESP method to forecast historical drought events (such as 2001, 2005 drought) and evaluated the performance of this method in the terms of predicting the drought severity. Figure 6 is one such plot shown below to demonstrate the potential for forecasting drought recovery periods. Given USBR's use of both medium range and seasonal climate predictions in decision-making, we have conducted preliminary evaluations of uses of two NOAA products in these areas for driving hydrologic predictions in the Yakima R. basin and for the State of Washington. Results were presented at scientific conferences. Figure 10 shows an example of downscaling NOAA Earth System's Research Lab medium range climate reforecasts for runoff prediction in the Yakima R. basin, and Figure 11 shows an example of the use of CPC seasonal outlooks for hydrologic prediction in Washington State.

TASK 4 (PENDING): **System evaluation** We will evaluate the outputs of the monitoring and prediction systems via retrospective comparison with USBR's own forecasts and with existing forecasts from the MMS system. Where streamflow biases are identified, bias-removal techniques based on percentile-mapping will be applied to improve the accuracy of the systems.

TASK 5 (CURRENT): **Decision context specification**. We have conducted meetings with key stakeholders (e.g., federal, state, and regional water officials, irrigation district managers, Yakima River Basin farmers) to understand the current organizational decision processes, current uses of forecast information, needs for NOAA forecast products, barriers to forecast use, and potential net benefits of using the NOAA-CPC forecasts and NOAA-based forecast information developed by this project. We also participated in monthly operations meetings in the USBR Yakima Field office and the Grape Wine Growers Annual Conference. We have identified specific decisions and decision makers that would use the forecast information. For example: According to irrigation district managers, farmers need forecast information in December and January (i.e., earlier than they currently receive forecast information, which is the first week of March) to make crucial crop management decisions for the upcoming year. Interestingly, irrigation district managers felt that earlier forecasts (i.e., before January) may not be as useful because of the possibility of large snow events during winter.

To date, we have developed a calendar of important water management events (Figure 7) and identified six key decision making realms that relate to these events (Figure 8). These provide a preliminary framework from which to define decision-making needs. The specific decision-making needs, and the timeframe for forecast information, depend on a number of factors, such as current conditions, timing, and location. For example, Roza Irrigation District has prorated water rights, which are frequently lost during drought, whereas Sunnyside Irrigation District has older, more guaranteed water rights. Therefore growers in Sunnyside are usually not required to cut back on water, even in dry conditions. However, in Roza Irrigation District, water managers need to know in March about possible conditions in the summer, so they can decide whether to hold off on using water for approximately three weeks in the beginning of the growing season to avoid depleting their water allocation before the end of the season.

TASK 6 (CURRENT): **Forecast specification and translation**. Through meetings with stakeholders, we have started to specify and create the needed forecast information (Figure 8); specifications include the relevant climate/hydrologic indicators, the lead time, the temporal scale of forecast, spatial scale of forecast, the required skill (including measures of skill relevant to decision-making), the format needed by decision-makers, and the links to impact mitigation. With regard to CPC seasonal forecasts, users expressed difficulties in using and understanding the forecasts (e.g., the interpretation of probabilities, and the accuracy of the forecasts). To overcome these difficulties, forecast products need to relate to how conditions are presently evaluated. Managers currently assess conditions based on comparisons with examples of past years. Managers at all levels of operations described current conditions based on analogies with previous years. That is, they want to know where things fit into the range of past averages and possible extremes. They also frequently reference and compare current conditions with specific years. For instance, 2001 is the year frequently referenced, because prorating was the lowest it has ever been (~37%). The drought, while unfortunate, nonetheless provided an important baseline that they reference. Decision makers weigh and merge information from multiple data sources to assess forecast uncertainty. Instead of evaluating the uncertainty of any particular forecast product, managers use multiple products to make decisions and, when products all point in the "same direction," they interpret this as increased certainty.

TASK 7 (CURRENT): **Forecast product use, integration, and refinement**
Through interacting with stakeholders, in individual interviews and monthly meetings, we have begun to account for the accuracy, usefulness, and limitations of forecast information. The degree to which managers care about and use weather and climate information depends on past precipitation events. In general, if a decision outcome uncertainty range includes adverse consequences, more information is sought. For example, system storage is a critical factor. Most management is based on the current reservoir levels. Therefore, in the winter, it may be difficult to define time periods that are of high concern to managers. If there happens to be a major precipitation event in the fall, daily/weekly forecasts throughout the winter are important and closely monitored. Until a precipitation event occurs, however, longer-term forecasts are more important than daily/weekly values (Figure 8, decisions 1 and 2). Certain reservoirs are more important than others, depending on the time of year. Yakima's system starts again each year, which makes management more dependent on current and seasonal conditions because the system lacks interannual storage capabilities.

TASK 8 (CURRENT): **Evaluation and communication** Preliminary feedback from water managers has been favorable on the decision-making realms (Figure 7 and 8), on the potential usefulness of contingency tables for directional skill measures (Figure 9), and the website http://www.hydro.washington.edu/forecast/sarp/. Figure 7 and 8 provided a useful approach, in discussions with managers, to identify important aspects of decision-making, such as when decisions are made, what are appropriate lead times, and which stakeholders are involved. Decision-making realms are likely to be further defined in the future, but these figures provide a basis for how this type of information might be displayed and used by stakeholders. The contingency tables provided a meaningful way to assess uncertainty, and it coincides with the "above normal" and "below normal" dichotomy that water managers use when comparing current conditions with past events. Managers were also interested in daily-updating soil moisture and SWE maps (Figure 3), especially because they provide information on how current conditions fit within the range of past events.

B. Summary of findings

From the users' perspectives, forecasts need to be tailored to their specific decision needs (i.e., annual crop decisions), and communicated with measures of accuracy and uncertainty that they can understand and trust.

C. List of any reports, papers, publications or presentations arising from this project; please send any reprints of journal articles as they appear in the literature. Indicate whether a paper is formally reviewed and published.

Publications:

Fontaine, M., and Steinemann, A.C. "Assessing Vulnerability to Natural Hazards: An Impact-Based Method and Application to Drought in Washington State," *ASCE Natural Hazards Review* (in press) 2008

Fontaine, M.M., Steinemann, A.C., and Hayes, M.J. State Drought Programs: Lessons and Recommendations from the Western U.S. *ASCE Natural Hazards Review* (in review)

Presentations:

Shukla, S., D. Alexander, A. Steinemann and A.W. Wood, NOAA Climate Prediction Applications Science Workshop (Seattle), Mar 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management In the Yakima River Basin of Washington State

Steinemann, A. Climate forecasts for drought management, NOAA Climate Prediction Applications Science Workshop (CPASW), Seattle, WA, March 21, 2007.

Fontaine, M, and Steinemann, A. Assessing and Mitigating Drought in Washington State, NOAA Climate Prediction Applications Science Workshop (CPAWS), poster, Seattle, WA, March 20-23, 2007.

Shukla, S., D. Alexander, A. Steinemann and A.W. Wood, Water Center Annual Review of Research (Seattle), Feb 2007, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management In the Yakima River Basin of Washington State

Wood, A., A. Steinemann, D. Alexander and S. Shukla, Fall American Geophysical Union Meeting (San Francisco), Dec 2006, Applications of Medium Range To Seasonal/Interannual Climate Forecasts For Water Resources Management In the Yakima River Basin of Washington State

Shukla, S. and A. W. Wood. Graduate Climate Conference (Seattle), Oct 2007,. Drought Monitoring: An Evaluation of Drought Indicators Based on Climate and Hydrologic Variables.

Vano, J.A., Graduate Climate Conference (Seattle), Oct 2007, Challenges and Rewards of Translating Climate Change Science for Non-scientists: Two Case Studies on Drought.

Wood, A., S. Shukla, J. Vano and A. Steinemann. Fall AGU Meeting (San Francisco), Dec 2007, Connecting climate, hydrologic and drought predictions to water resources management in Washington State.

Shukla, S. and A. W. Wood. Fall AGU Meeting (San Francisco), Dec 2007. Application of LDAS-era land surface models for drought characterization and prediction in Washington State. Vano, J.A. and A.C. Steinemann, Fall AGU Meeting (San Francisco), Dec 2007. Using Climate Forecast Information in Water Resource Planning: Opportunities and Challenges in the Yakima River Basin, Washington.

Shukla, S. and A. W. Wood. 88th AMS Annual Meeting (New Orleans), Jan 08. A Hydrologic Model-Based Drought Monitoring System for Washington State

Wood, A.W. N. Voisin and S. Shukla, 88th AMS Annual Meeting (New Orleans), Jan 08. A Medium-Range Ensemble Hydrologic Forecasting for Western Washington State

Shukla, S. and A. W. Wood. The Water Center Annual Review of Research (Seattle), Feb 2008. Application of A Land Surface Model for Drought Monitoring and Prediction In Washington State

Vano, J.A., Wood, A.W., Shukla S., and A.C. Steinemann, The Water Center Annual Review of Research (Seattle), Feb 2008. Connecting climate forecast information and drought predictions to water resource management: opportunities and challenges in the state of Washington.

Wood, A.W., Vano, J.A., Shukla, S., and A.C. Steinemann, NOAA Climate Prediction Application Science Workshop, (Chapel Hill, North Carolina), Mar 2008. Applications of climate forecast information in water resources management: opportunities and challenges in the Yakima River basin, Washington.

D. Discussion of any significant deviations from proposed workplan (e.g., shift in priorities following consultation with program manager, delayed fieldwork due to late arrival of funds, obstacles encountered during the course of the project that have impacted outcome delivery).

E. Where appropriate, describe the climate information products and forecasts considered in your project (both NOAA and non-NOAA); identify any specific feedback on the NOAA products that might be helpful for improvement.

Both climate and hydrologic predictions are being evaluated and utilized in this project. Two primary types of climate information are being used to drive hydrologic forecast ensembles, the streamflow component of which becomes input to water resources system models and decision approaches. Historical climate resampling, the first approach, is inherent in the Ensemble Streamflow Prediction (ESP) method of the National Weather Service River Forecast Centers. The second approach is to use seasonal precipitation and temperature ensembles based on NOAA NCEP Climate Prediction Center's new consolidated seasonal forecast, which underlies their official seasonal outlook. This product represents an experimental forecasting track that employs NCEP's state of the art techniques in the seasonal to interannual climate forecasting arena. This project is adding to the understanding of ways in which CPC climate and weather forecasts are used in water management operations by a primary water management agency in the western US. A recent presentations to CPC and other NOAA personnel at the NOAA CPAS Workshop highlighted findings from this effort.

III. Graphics: Please include the following graphics as attachments to your report

A. One Power point slide depicting the overall project framework/approach/results to date

B. If appropriate, additional graphic(s) or presentation(s) depicting any key research results thus far
(attached at end)

C. Photographs (if easy to obtain) from fieldwork to depict study information (if applicable).

IV. Website address for further information (if applicable)

http://www.hydro.washington.edu/forecast/sarp/

V. Additional relevant information not covered under the above categories.

PI Steinemann, through supplemental funding from the State of Washington (Department of Ecology, and Department of Community, Trade, and Economic Development) conducted additional activities that advanced the SARP goals; among them, working with state officials and water managers to improve the state drought plan (including the use of NOAA forecast information), and to reduce drought vulnerability throughout the state (again, using NOAA products). PI Steinemann has also continued collaborations with NIDIS (e.g., evaluating state drought plans in the 19 WGA states, and identifying needed monitoring and forecast products) and with RISAs (primarily the California Applications Program).

Co-PI Wood also contributed time to two NOAA-relevant activities that are related to SARP sectoral concerns: (a) Climate Change Science Plan Synthesis and Assessment Report 5.3: Decision support experiments and evaluations using seasonal to interannual forecasts and observational data, and (b) Workshop: Knowledge Systems for Sustainable Development Workshop on Climate Change Adaptation for Water Managers, Oracle, AZ, Feb. 2007.

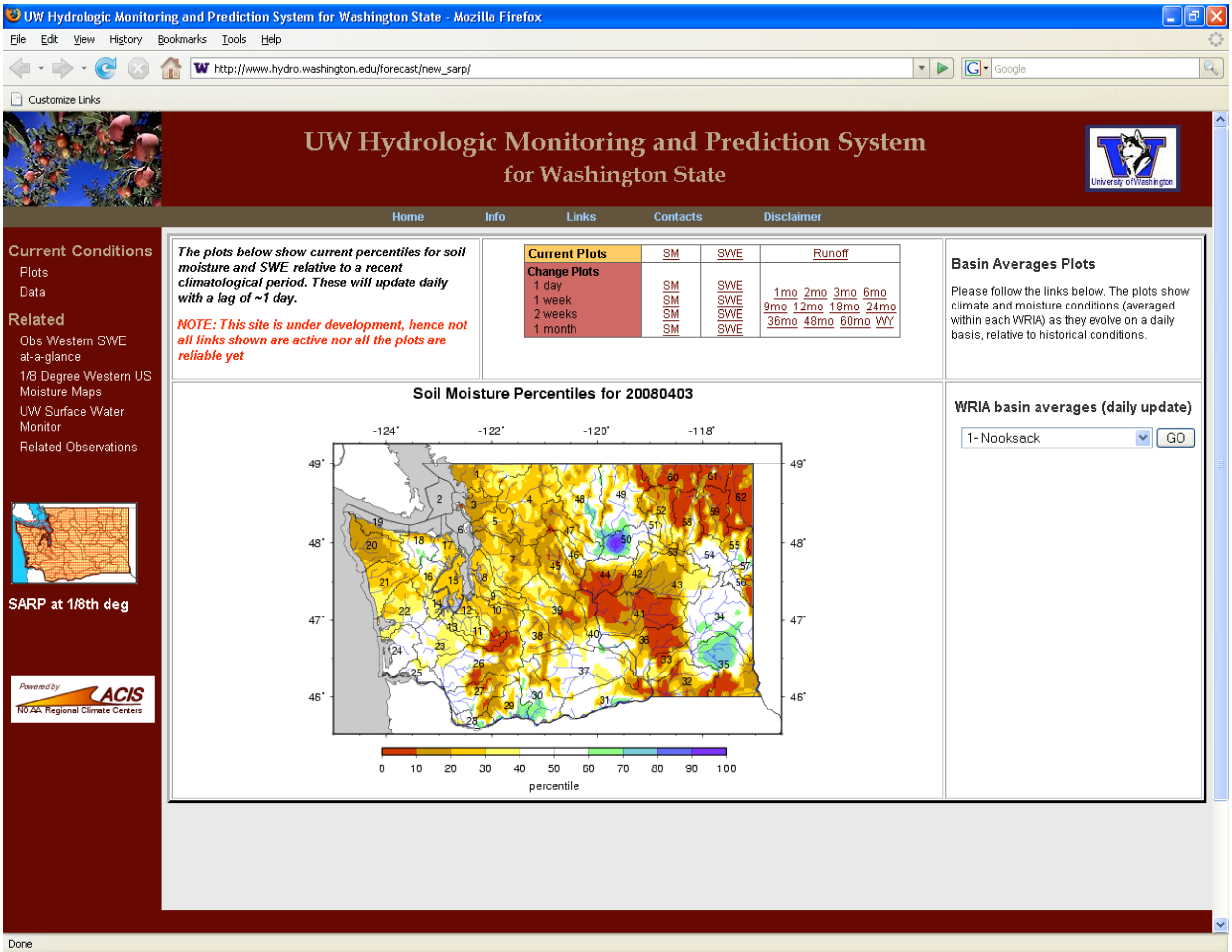

Figure 1: Website for the Washington State hydrologic monitoring system.

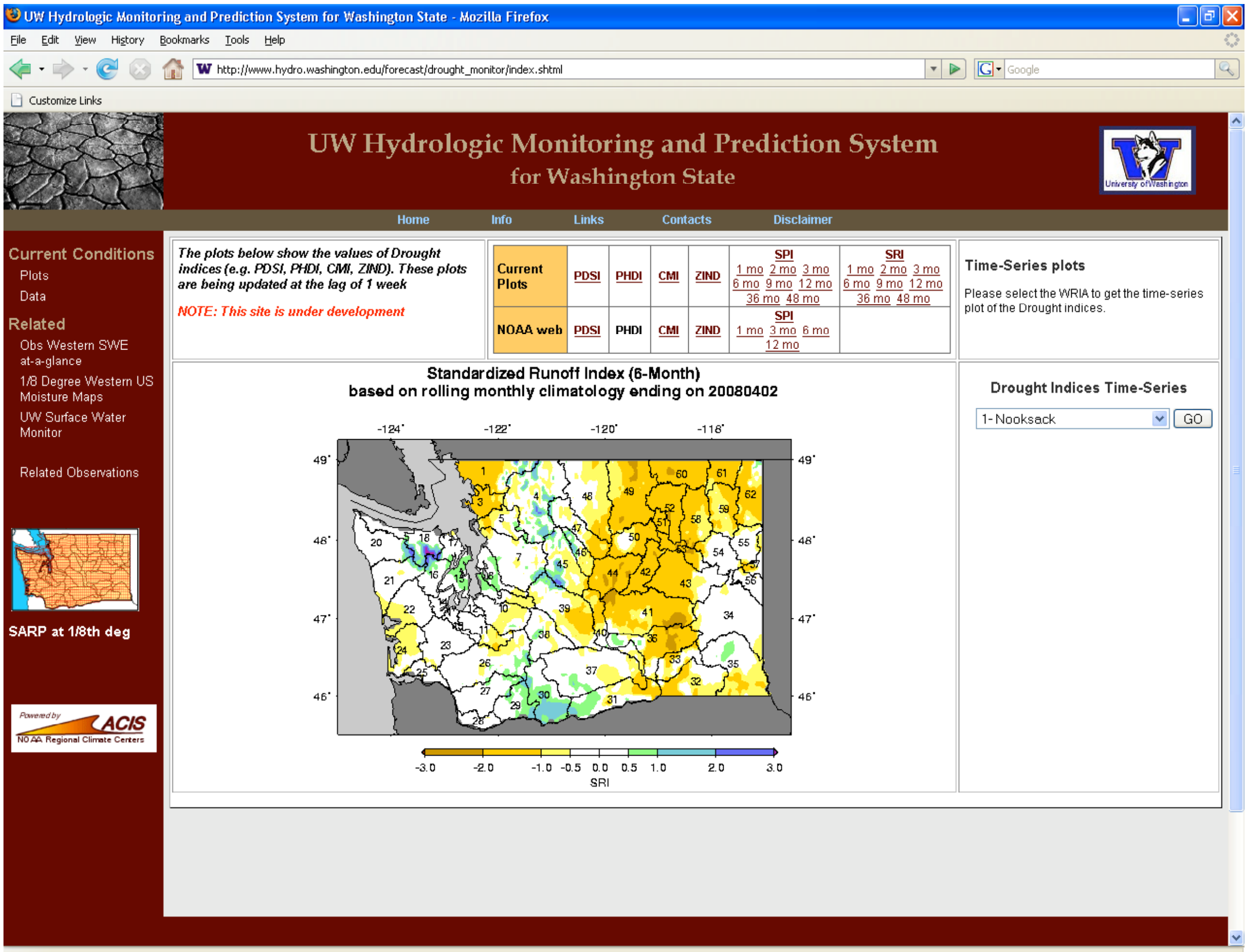

Fig. 2 Drought Indices Web-page

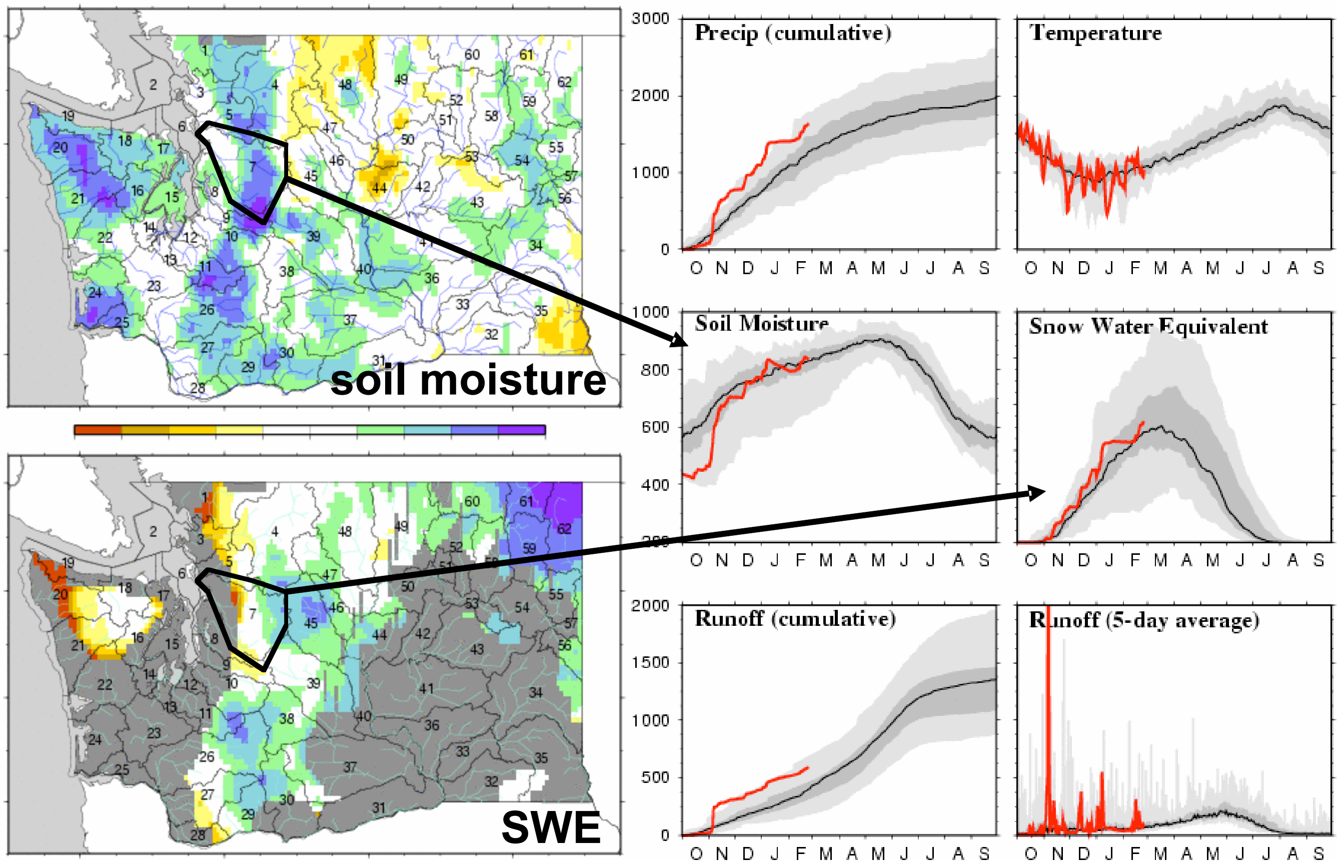

Figure 3: Daily-updating soil moisture and SWE maps for Washington State and associated hydrologic timeseries for each Water Resources Inventory Area.

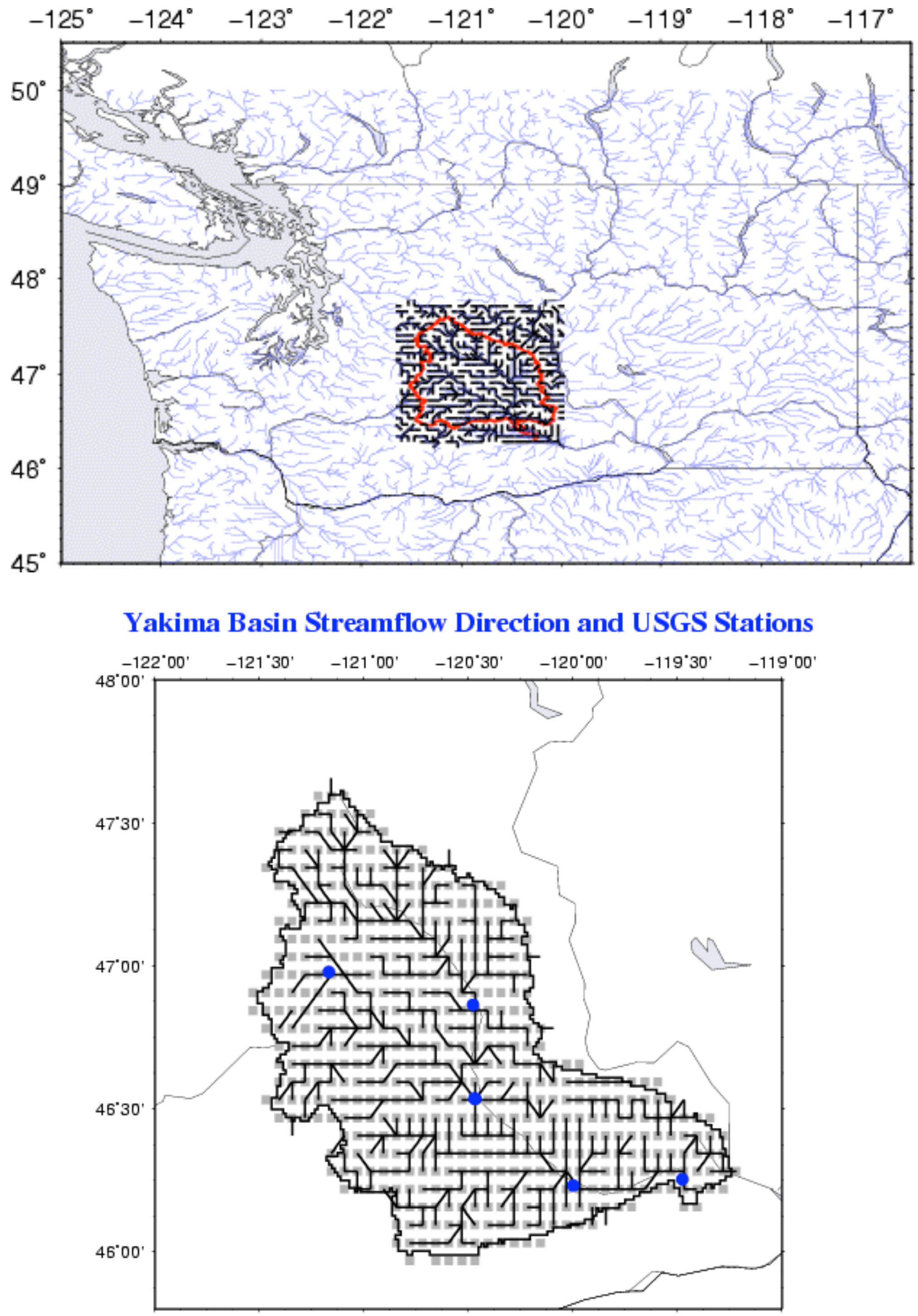

Figure 4: 1/16th degree flow routing network developed for the Yakima River basin focus area within Washington State. The basin's delineation is plotted in red.

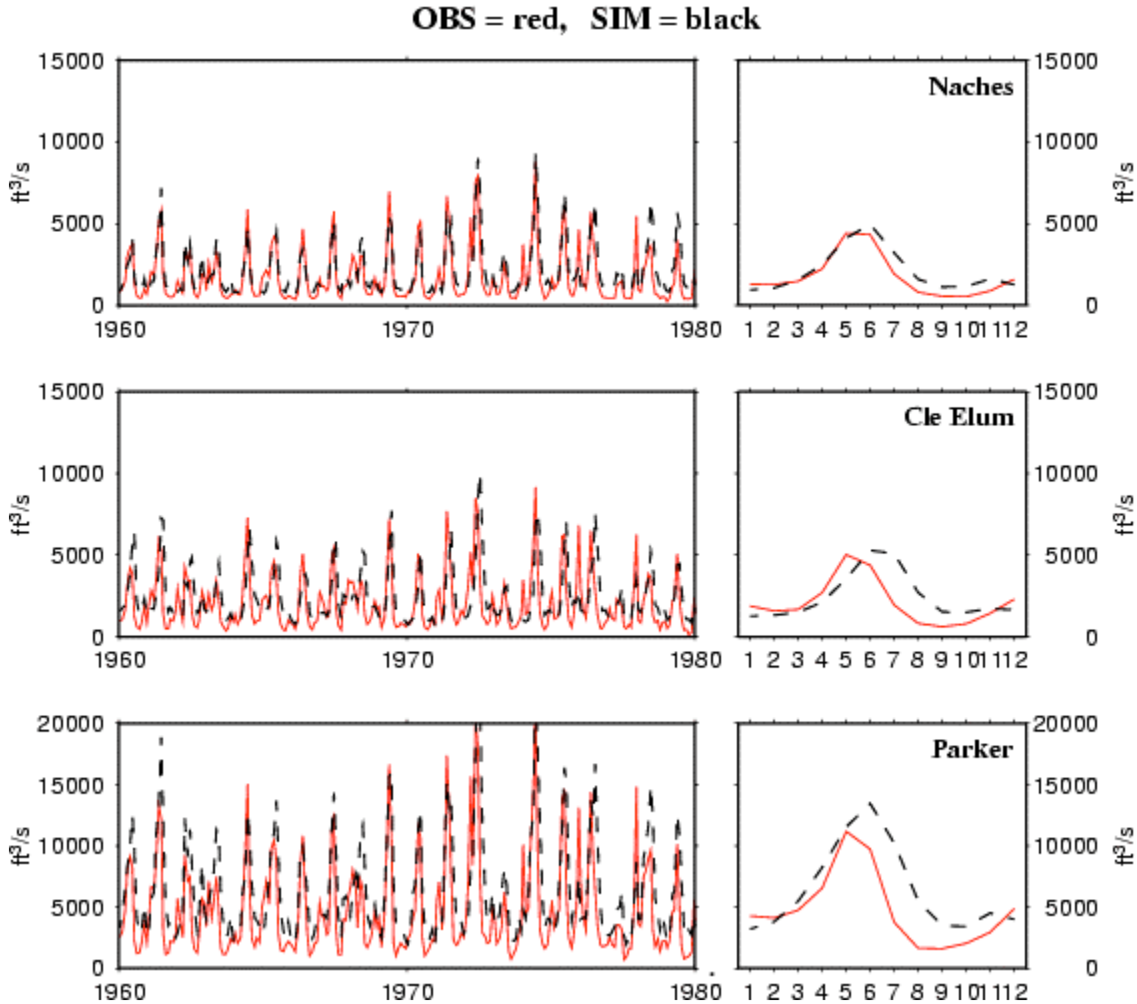

Figure 5: Preliminary calibration results for three streamflow forecast locations in the Yakima River basin (Naches River near Naches, WA; Yakima River at Cle Elum, WA; and Yakima River at Parker, WA).

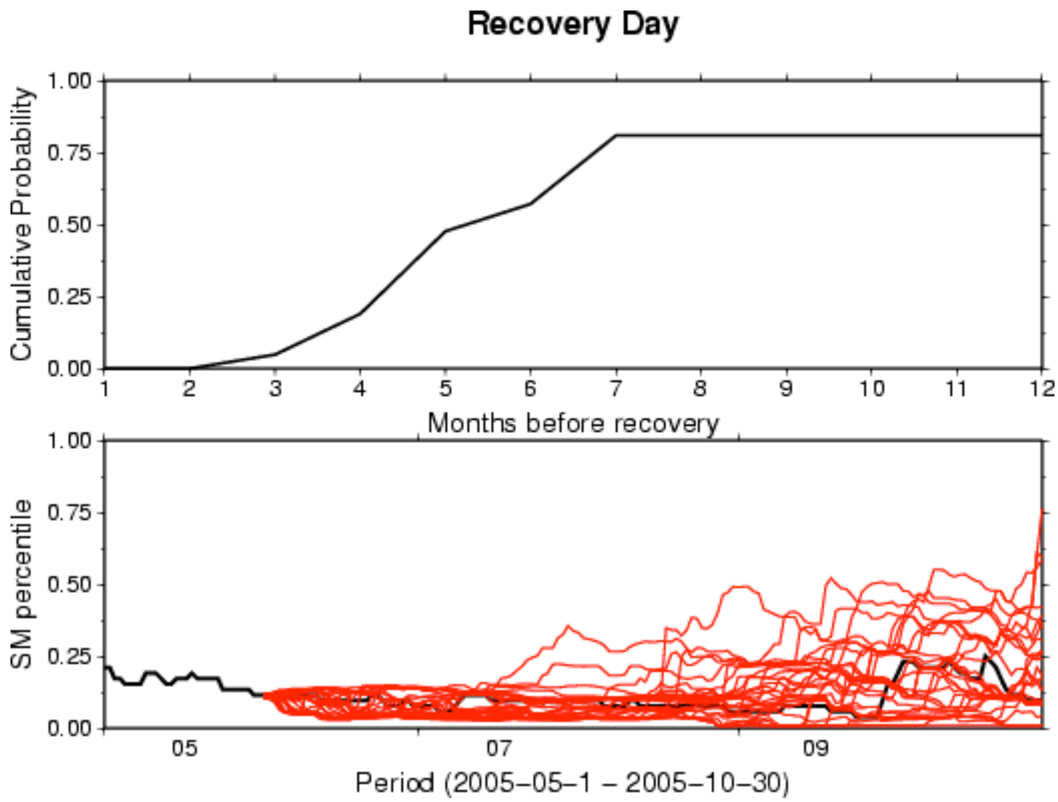

Fig. 6 Estimation of drought recovery period (Case- 2005 drought, starting from June 1, 2005)

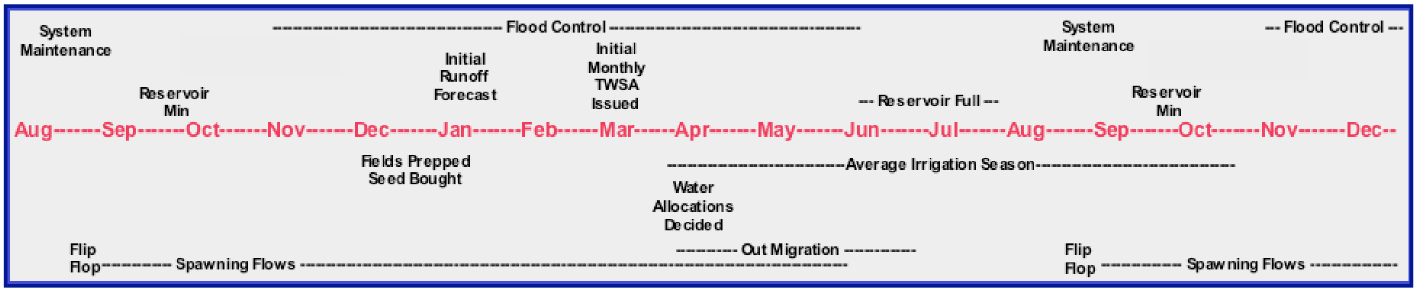

Figure 7. Yakima River basin event calendar
Management within the basin operates through a 15-month period, where water planning begins in August. Past year decisions, especially with irrigation allocations, carryover through December.

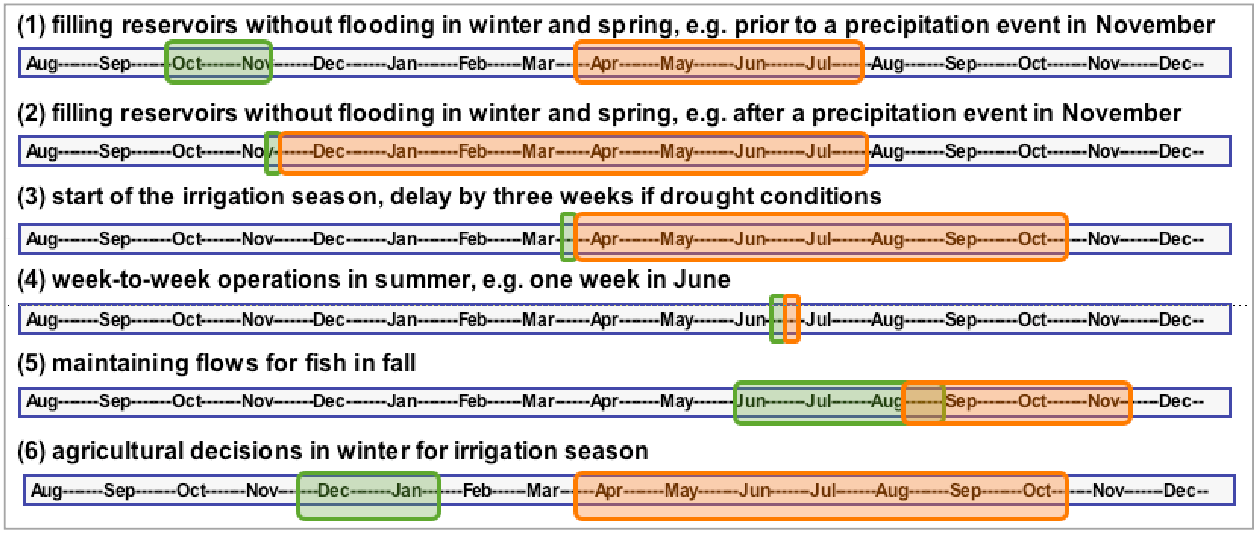

Figure 8. Decision-making calendar
Timelines indicate six decision-making realms that have been identified to date. Green circle = when decisions made, orange circles = time of forecast. Water management decisions have diverse climate information needs and the utility of forecasts vary greatly throughout the year.

Temperature

forecast \ observed	AN	BN
AN	69%	19%
BN	10%	2%

Precipitation

forecast \ observed	AN	BN
AN	28%	30%
BN	22%	20%

Figure 9. Example of Directional Skill Measurement Contingency Table
Values indicated the percentage of time the forecast is in the "right" direction, where AN=Above Normal and BN=Below Normal. Temperature is more skillful than precipitation according to this measure. These values are from the CPC Seasonal Forecast Climate Division 74 with a lead time of 0.5 month from 1995-2006.

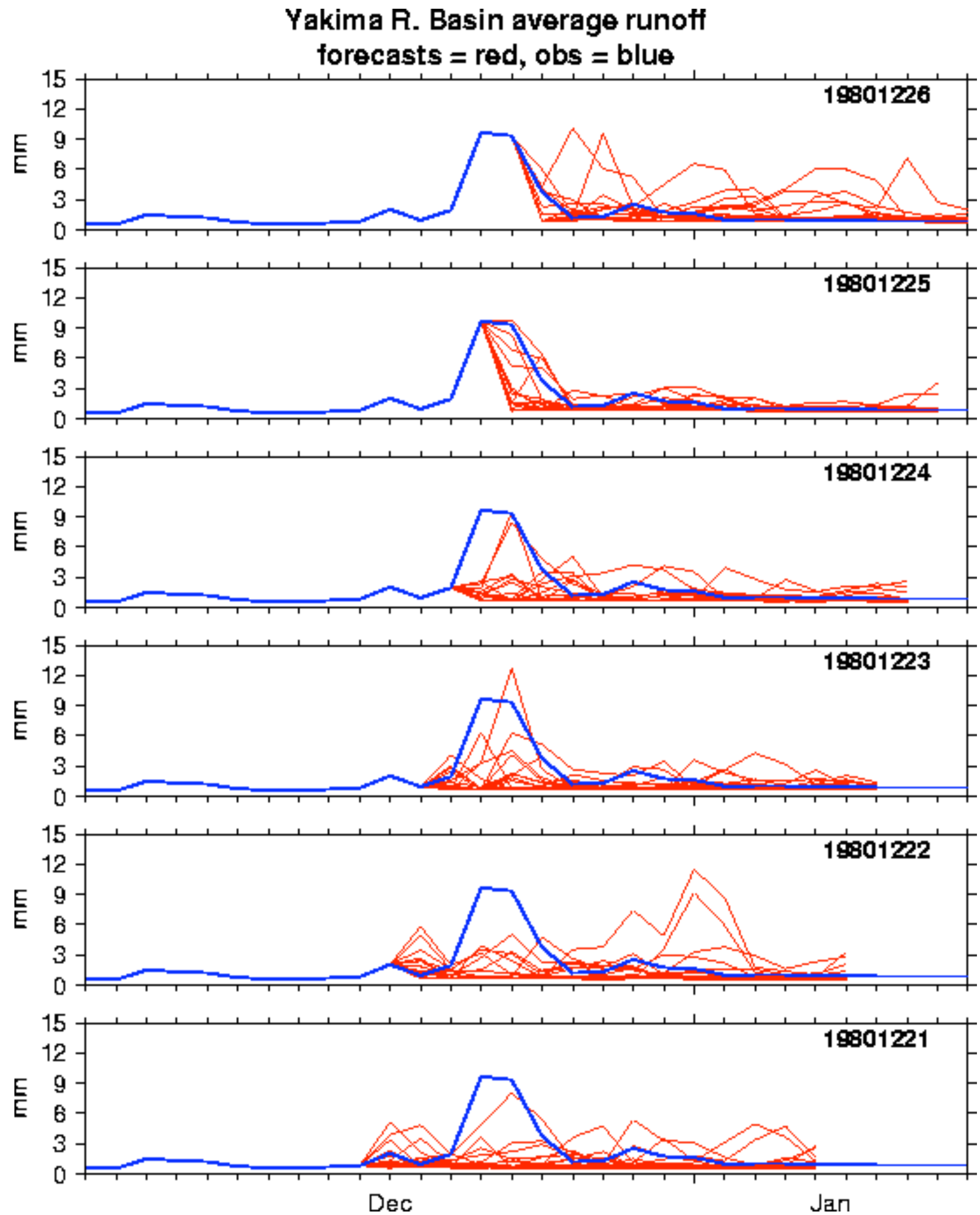

Figure 10. Example of retrospective assessment of the use of medium range (15 day) weather forecast from NOAA ESRL for forecasting Yakima R. flood event (from December 1980). From Wood et al. (2008) poster presentation at the AMS Annual Meeting, New Orleans, January.

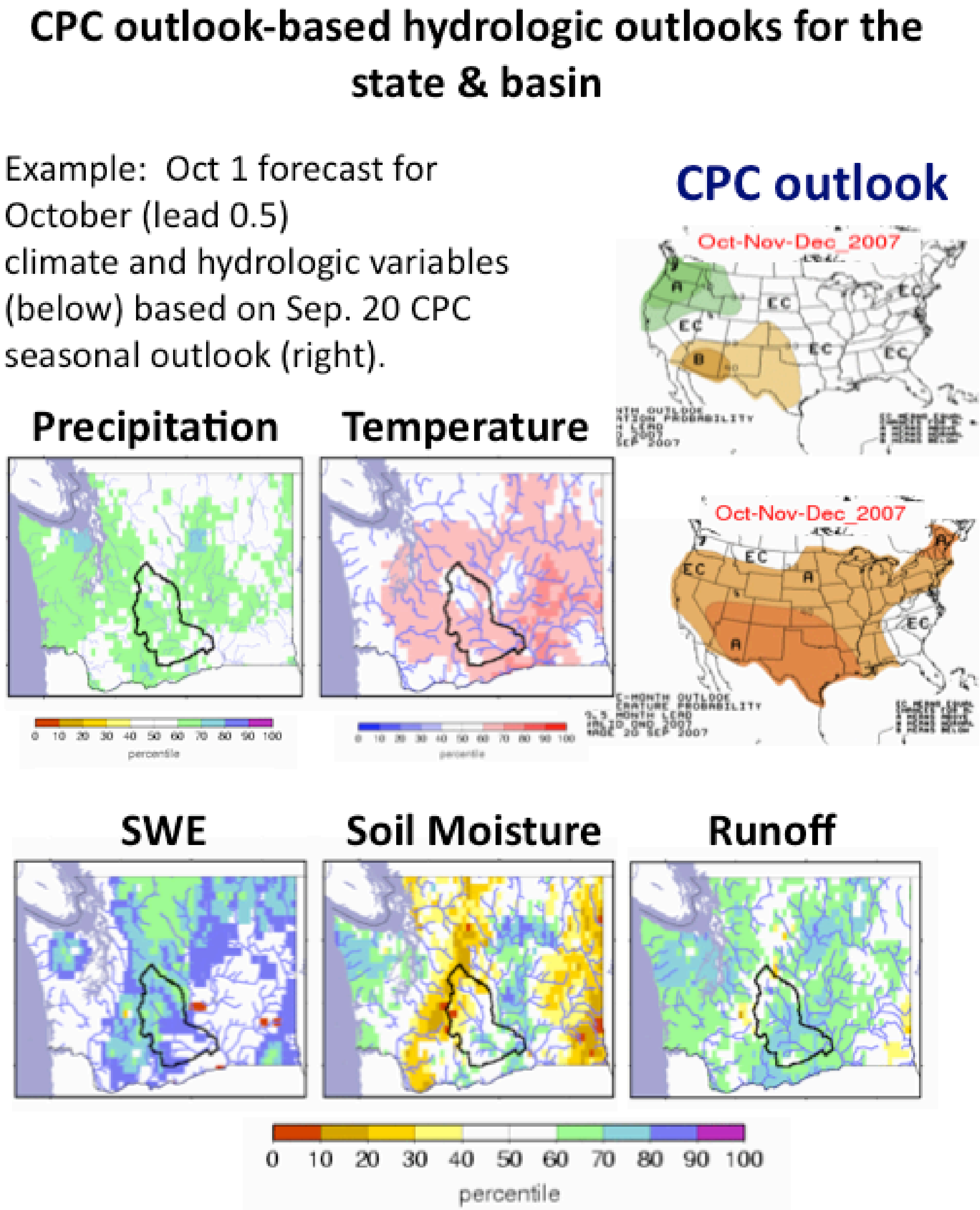

Figure 11. Example of a hydrologic evaluation of the use of CPC seasonal climate outlooks for hydrologic prediction at the Washington State scale. From Wood et al. (2007) poster presentation at the AGU Fall Meeting, San Francisco, December.